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t) INVESTIGATION OF SPUTTERING EFFECTS
ON THE MOON'S SURFACE

Third Quarterly Status Report,
NASA Contract NASw-751; Proj. 89308

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ABSTRACT

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Experiments to investigate the influence of bombardment of the

lunar surface by the solar wind were continued. Darkening of basalt

powder surfaces as a function of energy and duration of hydrogen ion

bombardment has been determined. Reflection curves for complex solid

mineral surfaces before and after bombardment have been measured.

The hole-drilling method of determining sputtering yields has been

extended to the oxides of Al, Ti, and Fe. *Author*

I. INTRODUCTION

The paper, "Modification of the Lunar Surface by the Solar-Wind Bombardment", submitted as the First Quarterly Status Report of this contract has been published in the November issue of Planetary and Space Science.[1] A letter describing our latest research results is being prepared for submission to the Journal of Geophysical Research.

We have continued to survey the literature for solar-wind and lunar surface data. Fielder[2] has published a paper supporting the importance of intrinsic erosion phenomena on the moon such as seismic and volcanic action. He concludes that intrinsic erosion is more important than extrinsic erosion such as cosmic-ray bombardment and micrometeorite impact. Solar-wind bombardment is not considered a major cause of extrinsic erosion.

Snyder, Neugebauer, and Rao[3] have published a paper on the correlation of solar-wind velocity with cosmic-ray variations and solar and geomagnetic activity. A strong correlation between increased plasma velocity and geomagnetic disturbances suggests the possibility that the abundant geomagnetic data will help settle the question of mean plasma velocity over large numbers of solar activity cycles.

In the third quarter the study of photometric properties of hydrogen-sputtered surfaces was continued. The degree of darkening of basalt powder has been determined as a function of energy and duration of ion bombardment. Normal albedos of various powdered materials before and after bombardment have been measured. The hole-drilling method of determining sputtering yields for metals has been

extended to metal oxides using a technique in which thin oxide foil
targets are prepared by pressing and compacting oxide powders.

II. SOLAR-WIND BOMBARDMENT OF BASALT POWDER

As reported in our Second Quarterly Status Report, the reflection
curve of a hydrogen bombarded powdered basalt surface closely resembles
that of the moon after bombardment times equivalent to $\sim 2 \times 10^5$ years
of solar-wind bombardment. We have now studied the situation for shorter
bombardment times and measured the change of the reflection curve and
the normal albedo as a function of bombardment duration. The samples
(insulating) are bombarded with hydrogen ions of average energy 500 eV
with a rf method described previously. Figure 1 is a photograph of
sputtered basalt samples illustrating the darkening. The approximate
equivalent duration of solar-wind action is also shown. The albedo is
measured normal to the surface with a phase angle between illuminator
and detector of $2\frac{1}{2}°$. As photographed, the samples in diffuse light
appear as they do to the eye, each one considerably darkened as the
duration is increased one order of magnitude, whereas the normal al-
bedo indicates the sharpness of the backscatter peak characteristic
of sputtered powder surfaces. Figure 2 is a similar photograph except
the samples have just been exposed to the plasma with the target elec-
trically floating. In this case, the target surface charges up nega-
tively and is bombarded by ions of much lower ion energy (probably not
exceeding 100 eV). The ion current density however remains the same.
We have no data on hydrogen sputtering yields at such low bombarding

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# DARKENING OF BASALT POWDER
BY SIMULATED SOLAR-WIND
BOMBARDMENT

Sputtering Duration		Normal Albedo
original		~ 0.27
3⅓ minutes (100 YR. EQUIV.)		0.16
33 minutes (10^3 YR. EQUIV.)		0.07
5½ hours (10^4 YR. EQUIV.)		0.05
55 hours (10^5 YR. EQUIV.)		0.06

FIGURE 1 - Darkening of Basalt Powder as a Function
of Hydrogen Ion Bombardment

DARKENING OF BASALT POWDER
BY HYDROGEN PLASMA EXPOSURE

Exposure Duration		Normal Albedo
original	⬤	~ 0.27
3⅓ minutes	⬤	0.25
33 minutes	⬤	0.18
5½ hours	⬤	0.12
55 hours	⬤	0.09

FIGURE 2 - Darkening of Basalt Powder as a Function
of Hydrogen Plasma Exposure

energies and therefore cannot correlate these results with actual solar-wind bombardment times. Physical sputtering at such low energies is probably negligible in the case of hydrogen and we believe that the effects here are more of a chemical or reactive nature. Experiments with powdered and solid surfaces, where a part of the surface is covered with a thin quartz foil, indicate that the darkening is certainly not due to ultraviolet radiation of wavelengths transmitted by quartz. Darkening by exposure to a plasma in noble gases is indeed very slight, or negligible, indicating the importance of chemical effects in the case of hydrogen.

Figures 3-6 are reflection curves of visible light for the surfaces illustrated in Figures 1 and 2. The angles of incidence i and reflection ϵ are measured from a normal to the surface. The backscatter is more pronounced on the sputtered surfaces than on the plasma-exposed surfaces. The curve for the equivalent of $\sim 2 \times 10^5$ years solar-wind action does not differ significantly from that for 10^5 years equivalent; therefore, we feel the surface has reached an equilibrium state.

III. SOLAR-WIND BOMBARDMENT OF SOLID SCORIA AND PUMICE

According to Hapke,[4] a complex, underdense surface is required of a material for it to have reflection properties similar to those of the moon. In an attempt to determine the effects of sputtering on solid but complex surfaces, flat scoria and pumice surfaces were bombarded by hydrogen ions for a period equivalent to 10^4 years solar-wind action. The reflection curves of these surfaces before and after bombardment are shown in Figures 7-10. Both surfaces are darkened by sputtering,
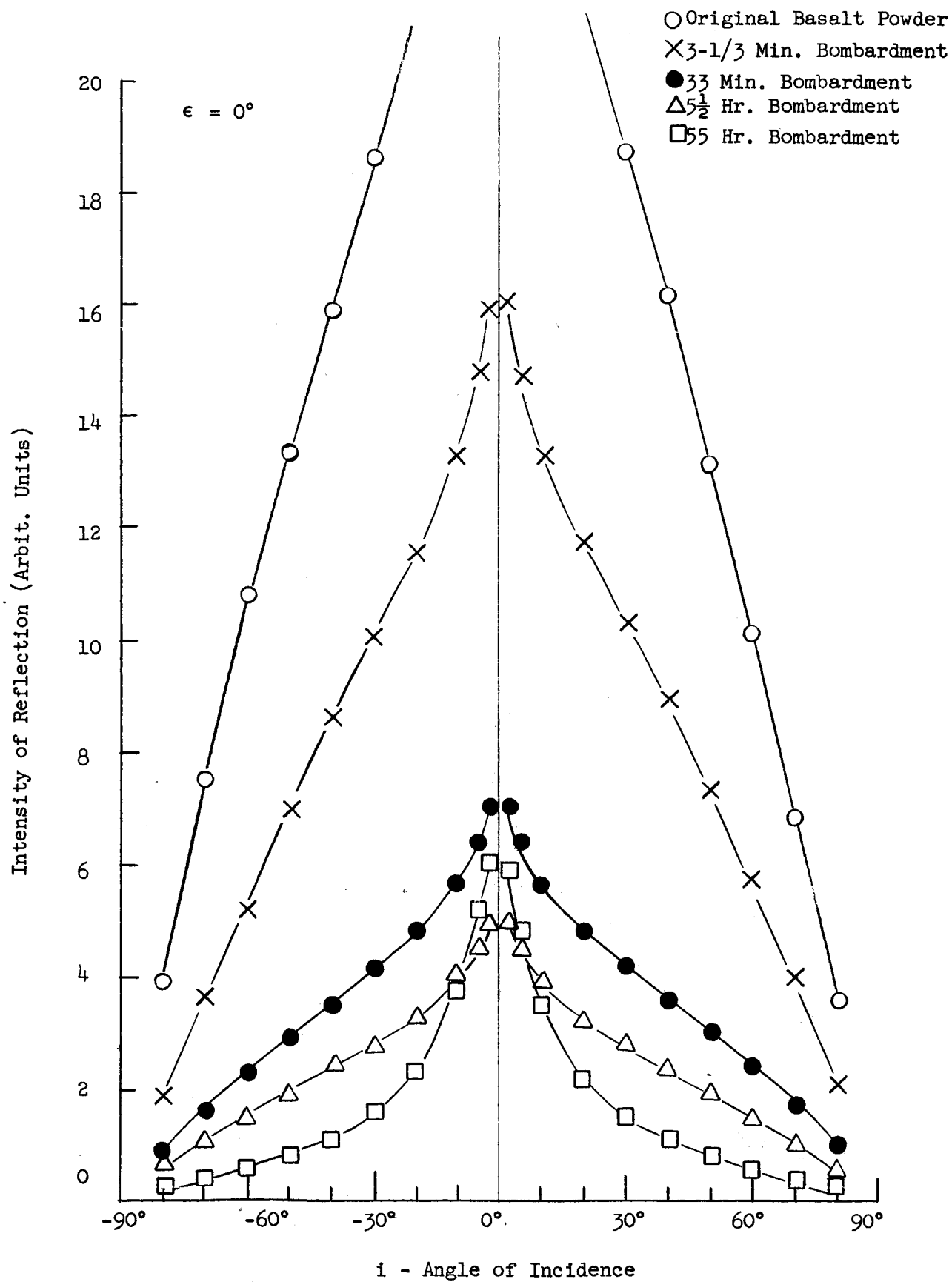
FIGURE 3 - Reflection Curves of Basalt Powder as a Function
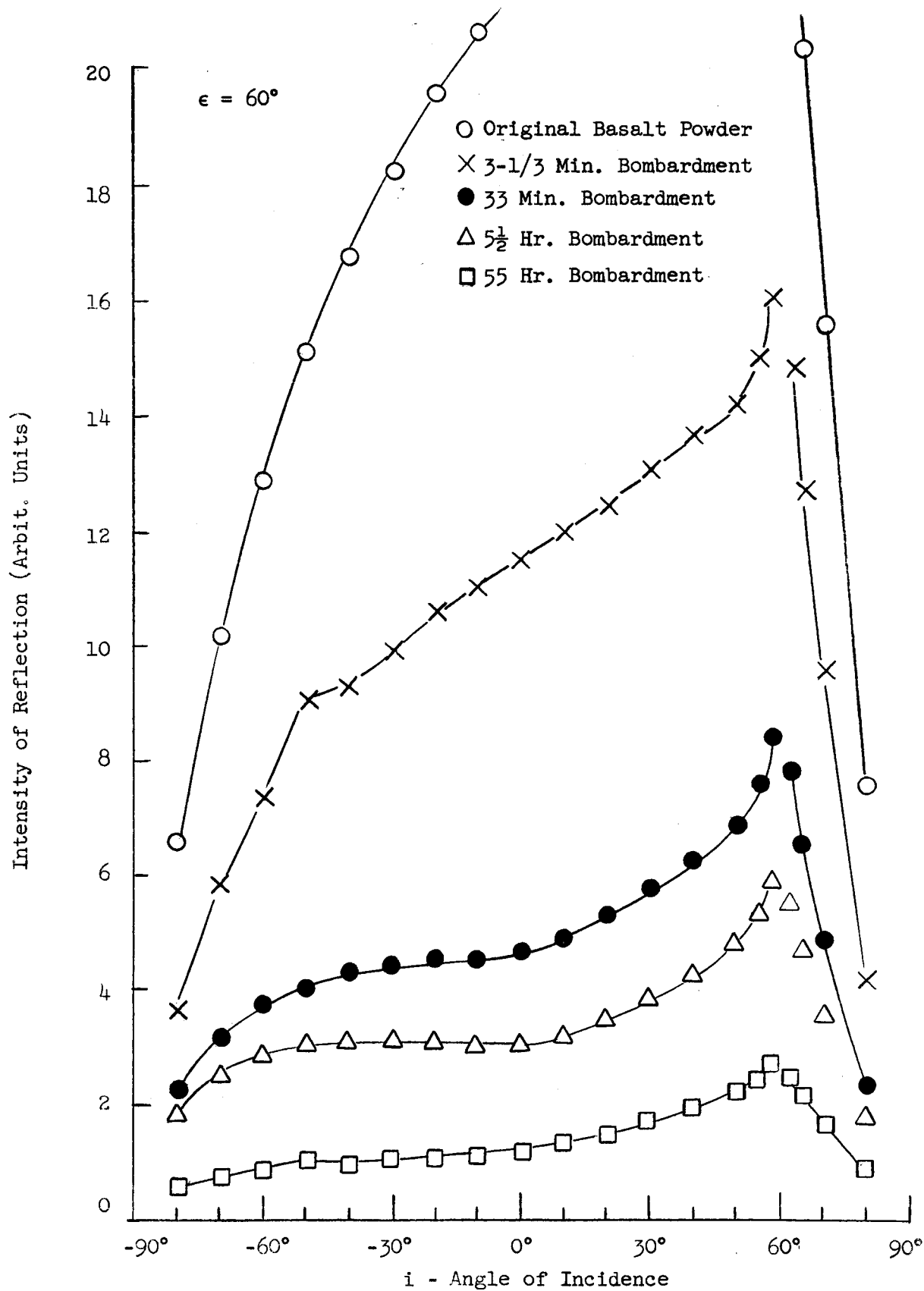of Hydrogen Ion Bombardment. ε = 0°.

FIGURE 4 - Reflection Curves of Basalt Powder as a Function
of Hydrogen Ion Bombardment. $\epsilon = 60°$.

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FIGURE 5 - Reflection Curves of Basalt Powder as a Function
of Hydrogen Plasma Exposure. $\epsilon = 0°$.
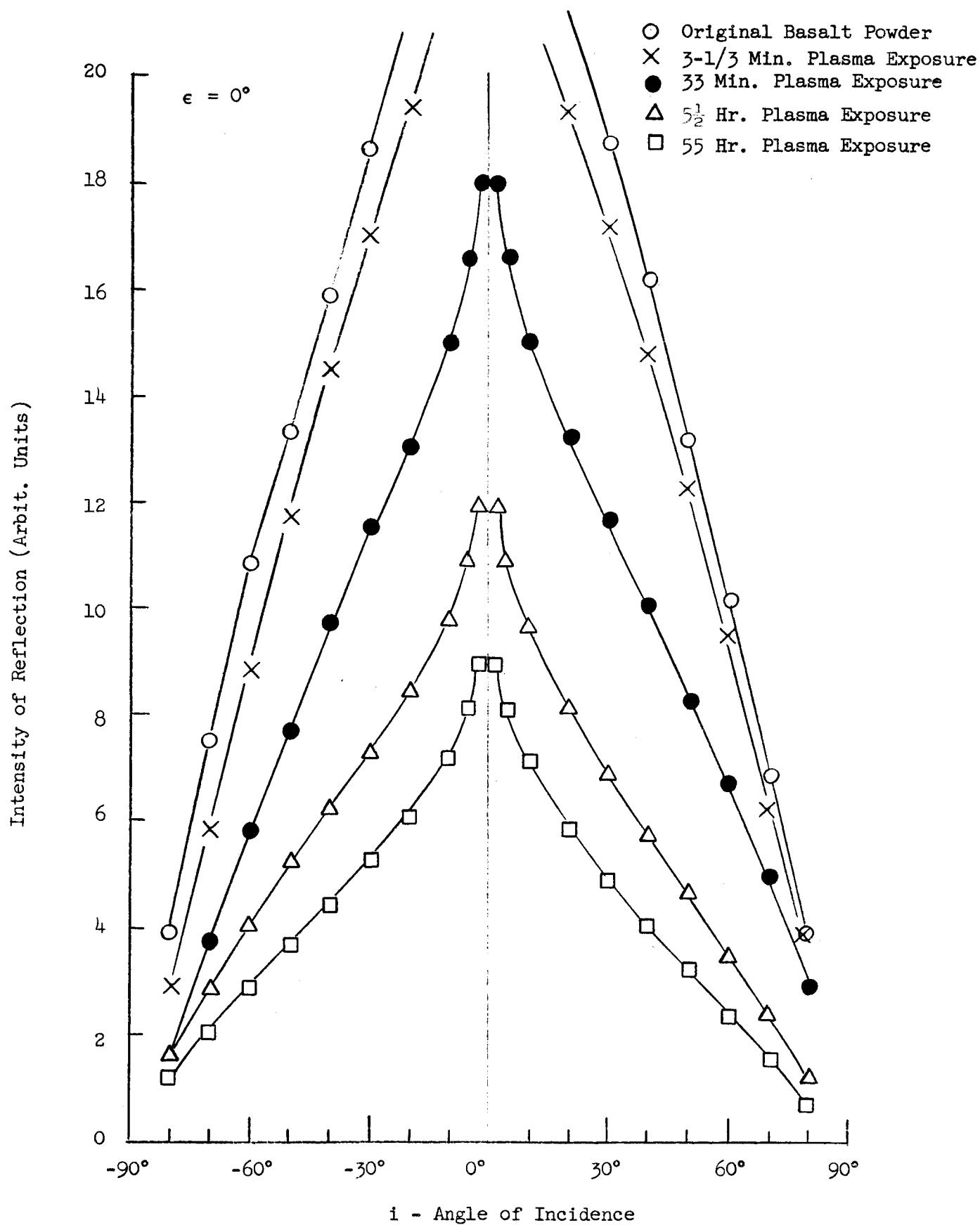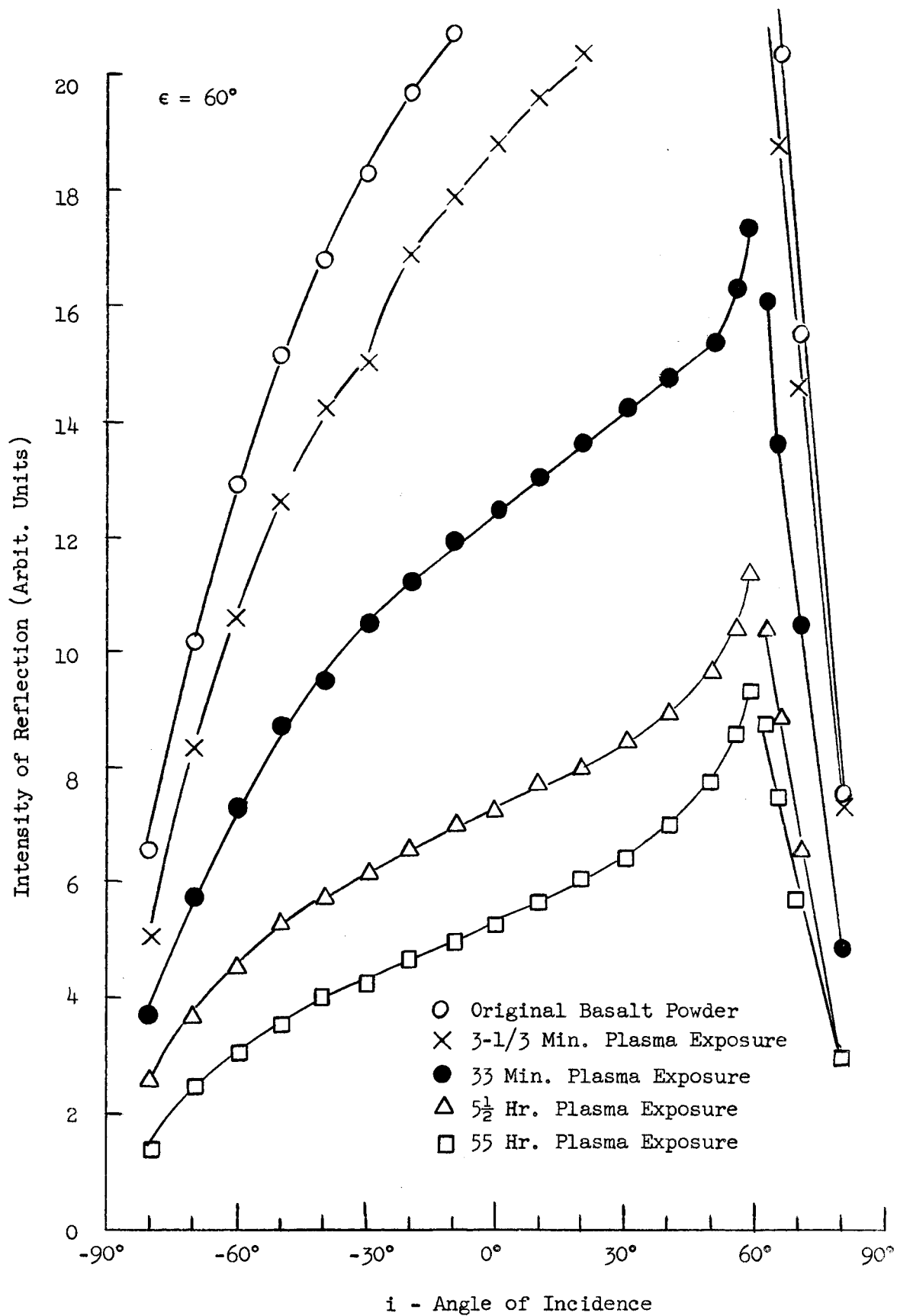
FIGURE 6 - Reflection Curves of Basalt Powder as a Function
of Hydrogen Plasma Exposure. $\epsilon = 60°$.

FIGURE 7 - Reflection Curves of a Solid Scoria Surface Before
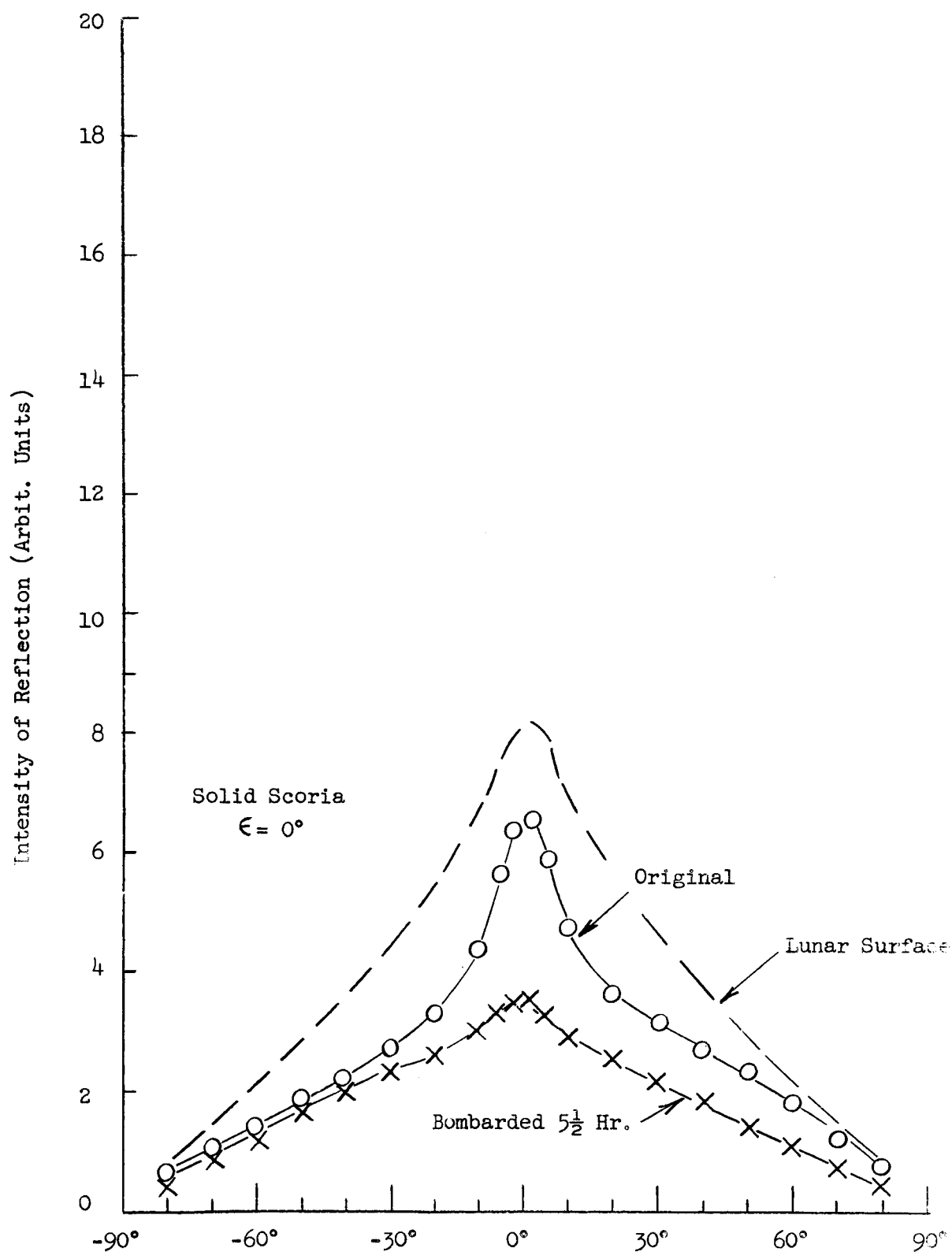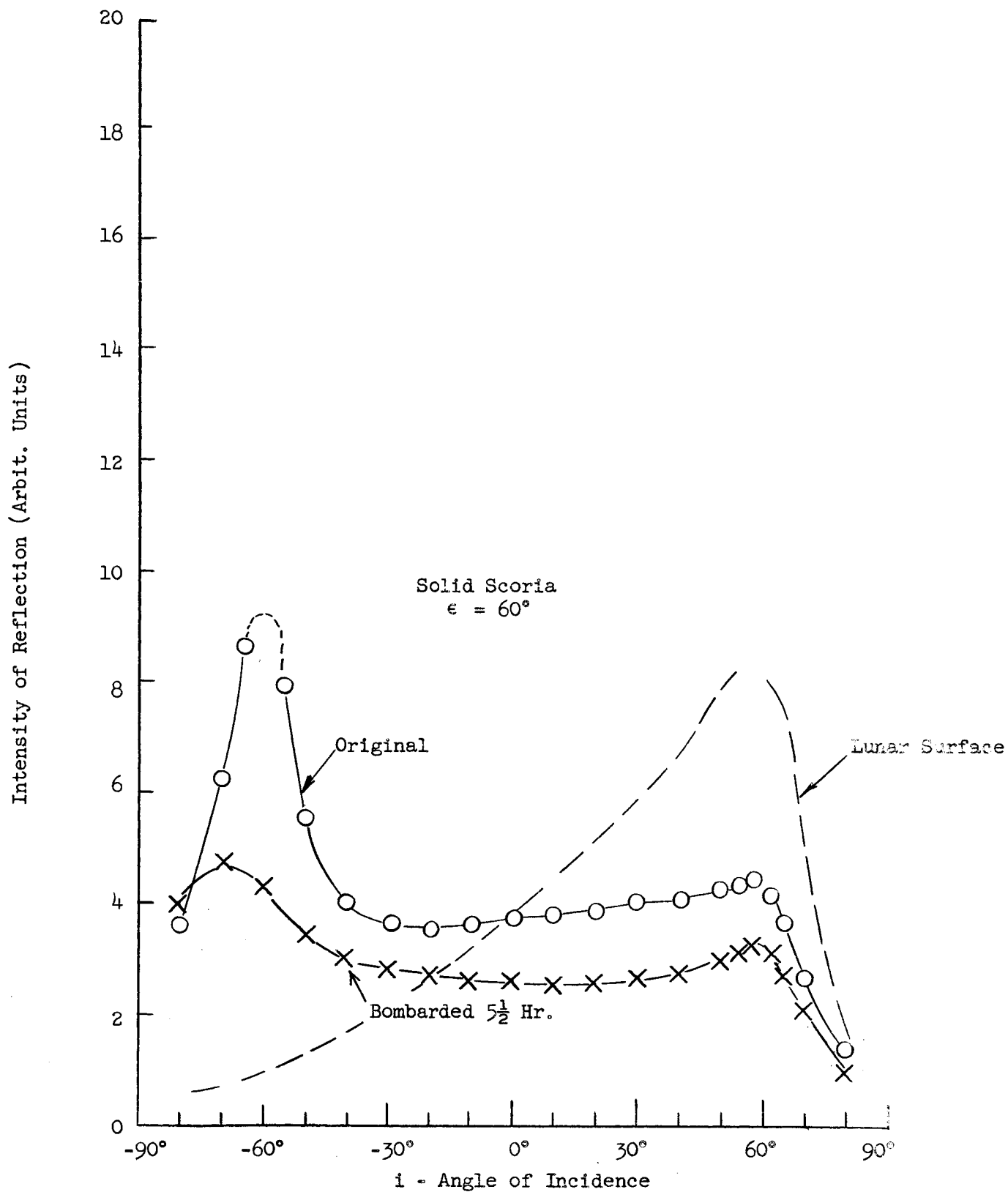and After Hydrogen Ion Bombardment. ε = 0°.

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FIGURE 8 - Reflection Curves of a Solid Scoria Surface Before
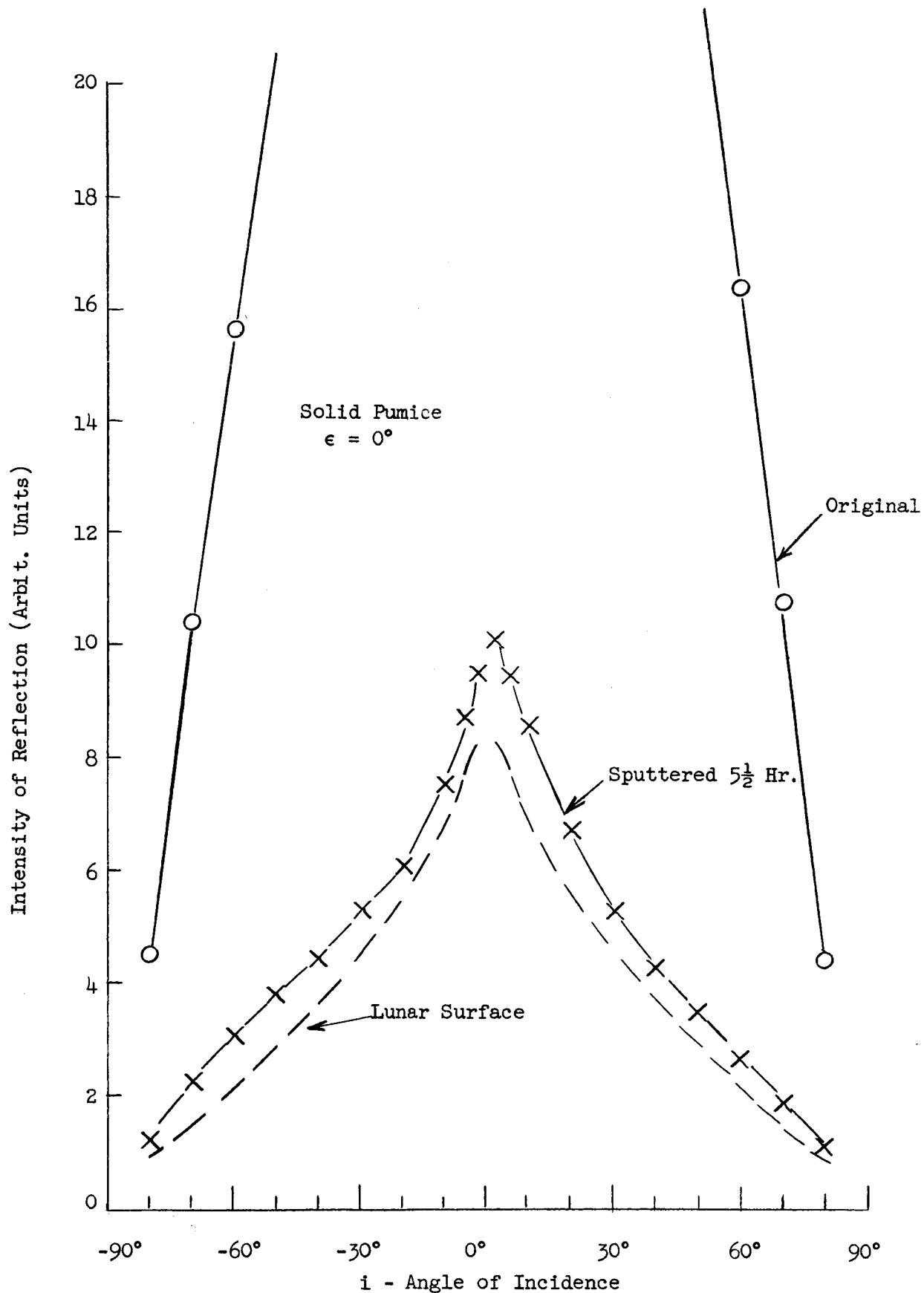and After Hydrogen Ion Bombardment. $\epsilon = 60°$.

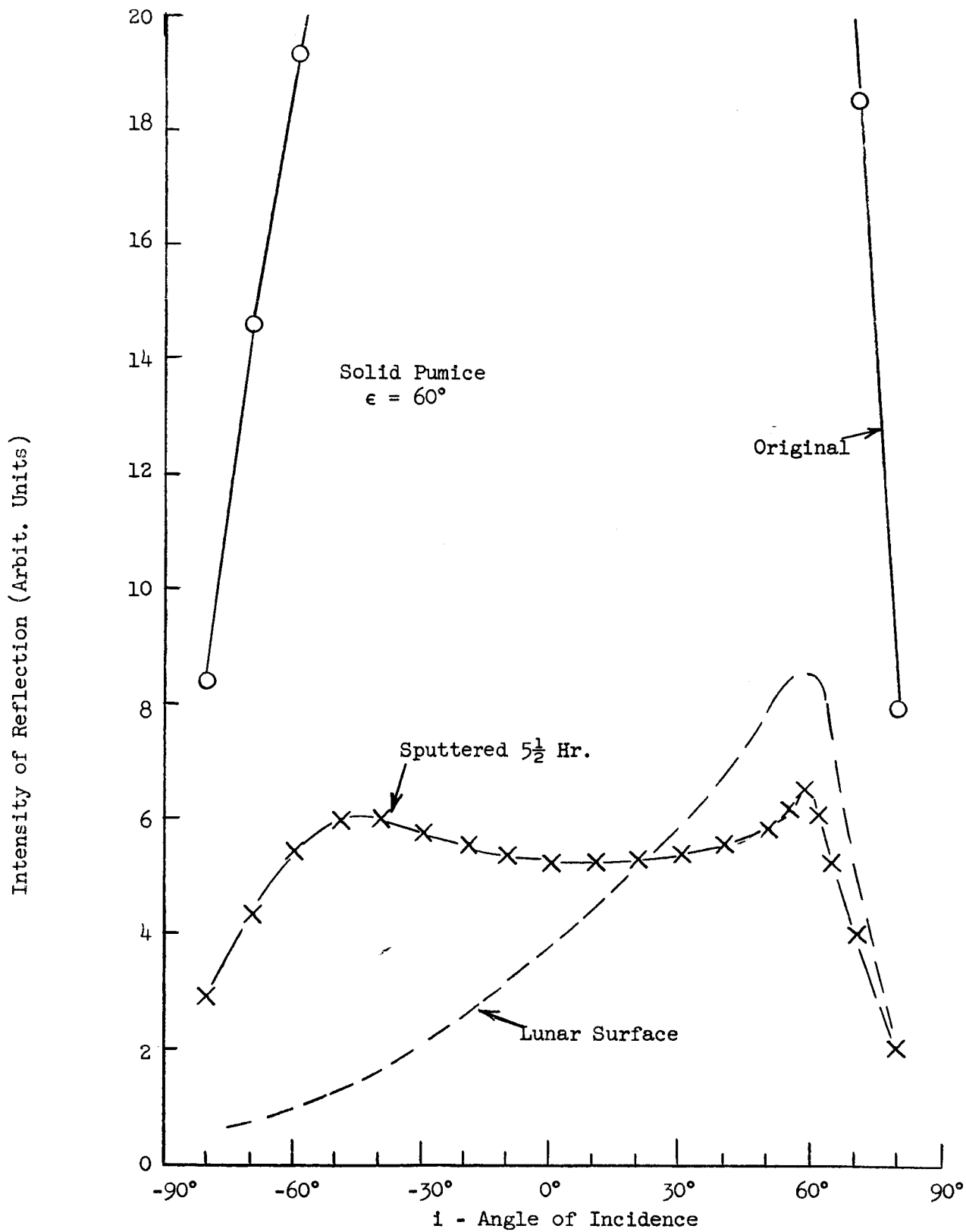FIGURE 9 - Reflection Curves of a Solid Pumice Surface Before and After Hydrogen Ion Bombardment. $\epsilon = 0°$.

FIGURE 10 - Reflection Curves of a Solid Pumice Surface Before
and After Hydrogen Ion Bombardment. $\epsilon = 60°$.

the normal albedo being reduced from 0.065 to 0.035 for scoria and

0.37 to 0.10 for pumice. With scoria, the most pronounced effect of

hydrogen bombardment is the reduction of the specular reflection

from the surface as indicated in the reduction of the backscatter

peak at $i = 0°$ in Figure 7 and in the $i = -60°$ peak in Figure 8.

The specular reflection peaks are still pronounced with both sur-

faces, but the changes in reflection characteristics due to sput-

tering tend to approach more the reflection curves of the moon.

As has been stated before, we believe the darkening is a com-

bination of physical and chemical effects. We have shown that

simulated solar-wind action on many terrestrial materials results

in a darkened surface of neutral color with pronounced backscatter.

IV. SPUTTERING YIELDS OF METAL OXIDES FOR HYDROGEN IONS

The hole-drilling method previously used to obtain sputtering

yields of metals with mass-analyzed hydrogen beams has been extended

to the oxides of metals by the development of techniques for preparing

oxide foils.

Since the composition and area density of the foil must be known,

the technique must permit determination of each quantity. The method

of baking at high temperatures in the presence of oxygen is adequate

for metals of high melting point and relatively high chemical activity.

Thus Ti and Fe foils were cut to size, placed on quartz, and baked in

air for several hours at 1000°C. Some difficulty was experienced with

curling of the foils and sticking to the quartz, but those foils that

curled such that only the corners stuck to the quartz could be broken

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loose and used. The oxygen content was obtained from the increase
in area density. The foils became essentially TiO_2 and Fe_2O_3, the
highest oxidation states. The latter substance is non-magnetic as
was the foil.

The second method is the compacting of fine powders of a known
substance, in this case Al_2O_3 and Fe_2O_3, into a self-supporting foil.
The powders were spread thinly, and as uniformly as possible on a
Ag foil, a 4 x 10 mm rectangle. The foil and powder were compressed
between accurately parallel, polished steel surfaces to an estimated
16,000 atmospheres. The resultant powder foil was self-supporting
over the 4 x 10 mm rectangle, while the spilled-over powder could
be brushed away from its edge. The strongly-compressed rectangle
of powder had undergone a marked color change to darker shades and
its surface was shiny. Furthermore, it readily separated from the
Ag foil. The use of a Ni foil to define the area of high pressure
was not satisfactory because the powder foil tended to show numerous
cracks leading in from the edge toward the central region. The
softer Ag foil produced few such cracks in the powder foil. Both
the Ni and Ag foils were about $25\,\mu$ thick.

A calculable thickness of Ni (about $9\,\mu$) was sputtered on one
side of the oxide foils to provide additional strength and a path
for heat and electrical current from the ion-bombarded area of the
foil to its edge. The Ni film faces away from the bombarding
mass-analyzed hydrogen ion beams so that it will not be sputtered
away from the edge of the hole being drilled. The Ni film is

thick enough to keep the foil temperature at the hole below 500°C; thermal fracture has not been observed.

Foils of quartz have been previously studied by cutting fragments from a large bubble of quartz. But silicon metal could not be obtained as a foil. It is expected that both Si and SiO_2 can be prepared by the powder foil method so that a direct comparison can be made and the role of chemical effects elucidated.

The results are presented in Table I. It should be noted that for each run the ratio $Y_3 : Y_2 \cong 3:2$. This result is a general feature for this energy range of hydrogen sputtering and can be used as a rough check on the uniformity in thickness of the powder foils. Secondly, the oxide yields are decidedly reduced for Al (x .3), Ti (x .7), and Fe (x .4) when expressed as metal atom/hydrogen ion as they are given in the table. We have observed that metal oxides have yields that are lower than the corresponding metals by an order of magnitude when bombarded by low-energy, noble-gas ions. The fact that the reductions here are rather nearer one half suggests the possibility of chemical removal of oxygen. But oxygen is not removed so very readily that its effect is negligible. The correlation to the heats of formation of the respective oxides, as given in Table II, is not obvious. Results are being repeated for verification.

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TABLE I

SPUTTERING YIELDS FOR 7 keV H_2^+ AND H_3^+ IONS

Metal	Y_2 x 10^3	Y_3 x 10^3	Oxide	Y_2 x 10^3	Y_3 x 10^3	Preparation
Al	29 ± 1	42 ± 1.5	$AlO_{3/2}$	10.5 ± 1	15.0 ± 1.5	Powder
				11.8 ± 0.5	17.1 ± 1	Powder
Ti	10.9± 0.3	15.3± 0.5	TiO_2	7.5 ± 0.4	12.9± 0.6	Baked
Fe	24 ± 1	33 ± 1.5	$FeO_{3/2}$	12.7 ± 0.6	20.4 ± 1	Baked
			$FeO_{3/2}$	9.4 ± 1	12.8 ± 1	Powder
			SiO_2	19 ± 2	34 ± 3	Foil

TABLE II

HEATS OF FORMATION

$AlO_{3/2}$	199.5 kcal/mole
TiO_2	218.0
$FeO_{3/2}$	98.2
SiO_2	205.4

LIST OF REFERENCES

1. Wehner, G. K., C. E. KenKnight, and D. L. Rosenberg. Modification of the lunar surface by the solar-wind bombardment. Planetary Space Sci. 11: 1257-61 (1963).

2. Fielder, G. Erosion and deposition on the moon. Planetary Space Sci. 11: 1335-40 (1963).

3. Snyder, C. W., M. Neugebauer, and U. R. Rao. The solar wind velocity and its correlation with cosmic-ray variations and with solar and geomagnetic activity. J. Geophys. Res. 68: 6361-70 (1963).

4. Hapke, B. W. A theoretical photometric function for the lunar surface. J. Geophys. Res. 68: 4571-86 (1963).